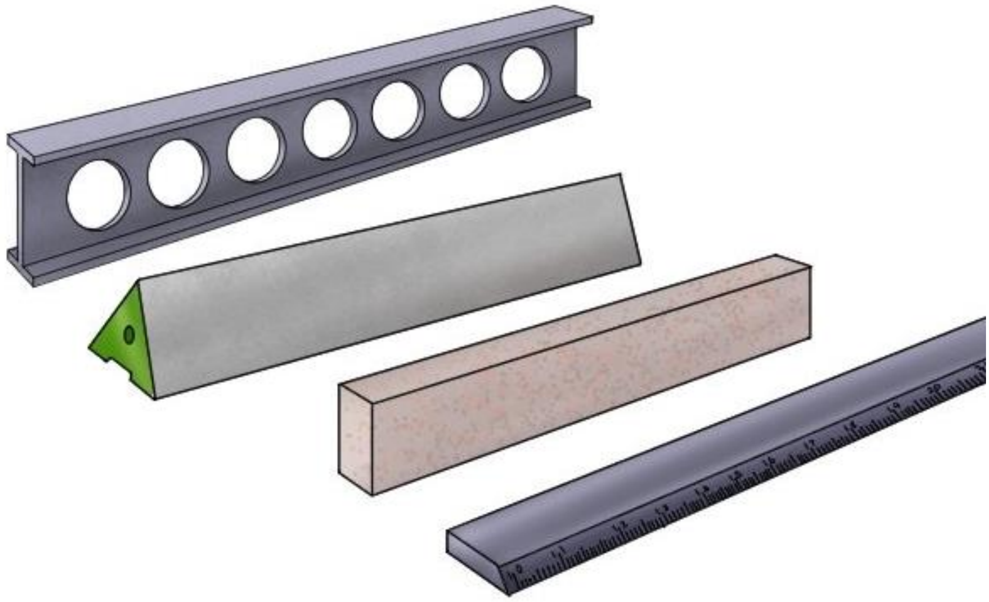
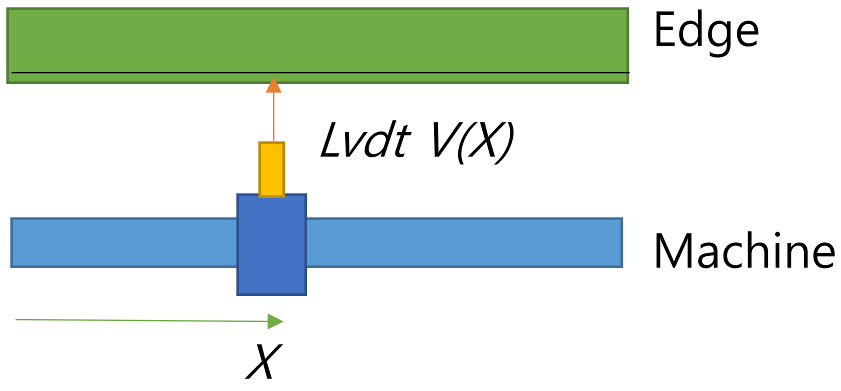
Precision Metrology 13- Straightness Measurement

Straightness measurement using the Straight Edge

Straight edge: Artefact of precision straight line feature, made of steel (by grinding/lapping), cast iron(by scraping), granite(by lapping). Typical sizes are 300mm, 600mm,1m, etc. Few um tolerance per 1 metre, typically.



Source: wonkee-donkee tools(UK)



Sign convention: + for away; – for near

When M(X) is the machine's straightness profile, and V(X) is the measured profile at X location by the LVDT or Capacitance gauge along the machine axis.

The measured profile, V(X), is

$$V(X) = - M(X) + aX + b$$

where a, b are the slope and offset; and the slope and offset can be physically interpreted as the non-parallelism and stand-offs encountered during the set-up procedure

Because the straightness error is the deviation from the reference straight line, thus the 3 methods of reference fitting techniques such as the end-points fit, least squares fit, and the minimum zone fit can be applied to calculate the slope and offset. Calculation of a, b can be used to obtain pure straightness error after removing the slope and offset effects,

$\underline{V}=V(X) - aX - b\ (= - M(X))$

$\therefore$ The straightness error=max $\underline{V}$ - min $\underline{V}$

(Q: Straight edge is really straight?)

Reversal Technique for Straightness Measurement

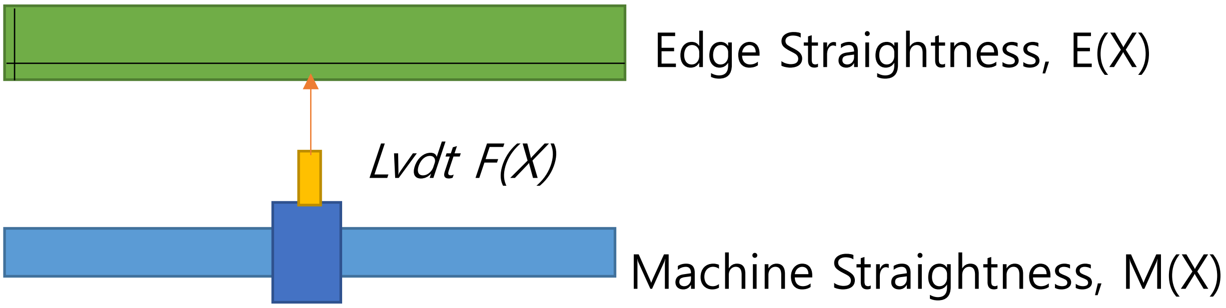
:To eliminate the straightness error, or self-error, of the straight edge. F type and M type measurement methods

1.F type measurement method

:Fixed edge type measurement method

Sign convention: + for away; – for near

Forward measurement

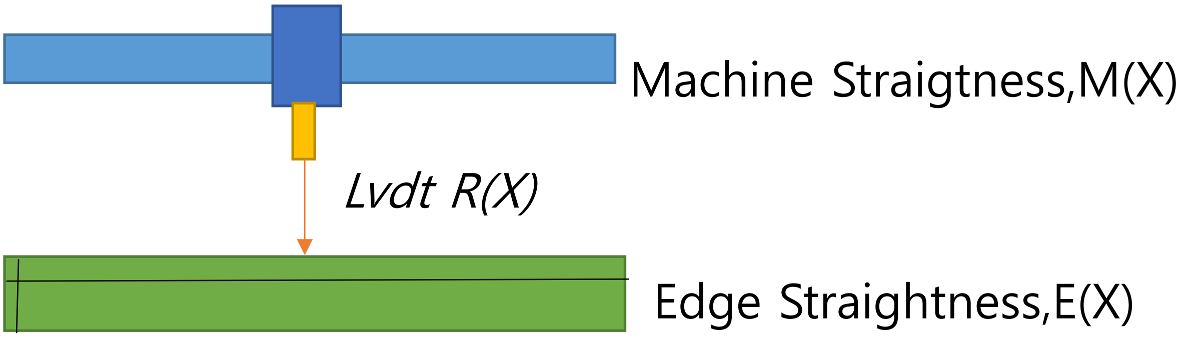


Forward measurement, $F(X) = -E(X) - M(X) + a_F X + b_F$

where a_F, b_F are slope and offset of the best fit line, and from the non-parallelism and stand-offs.

Thus, $\underline{F} = F(X) - (a_F X + b_F) = -E(X) - M(X)$ (1)

Reverse Measurement



Reverse measurement, $R(X) = -E(X) + M(X) + a_R X + b_R$

where a_R,b_R are slope and offset of the best fit line, and from the non-parallelism and stand-offs.

Similarly, $\underline{R} = R(X) - (a_R X+b_R)=-E(X)+M(X) \quad (2)$

From (1)+(2) and (1)-(2)

$E(X)$=Edge straightness=$-(\underline{F}+\underline{R})/2$

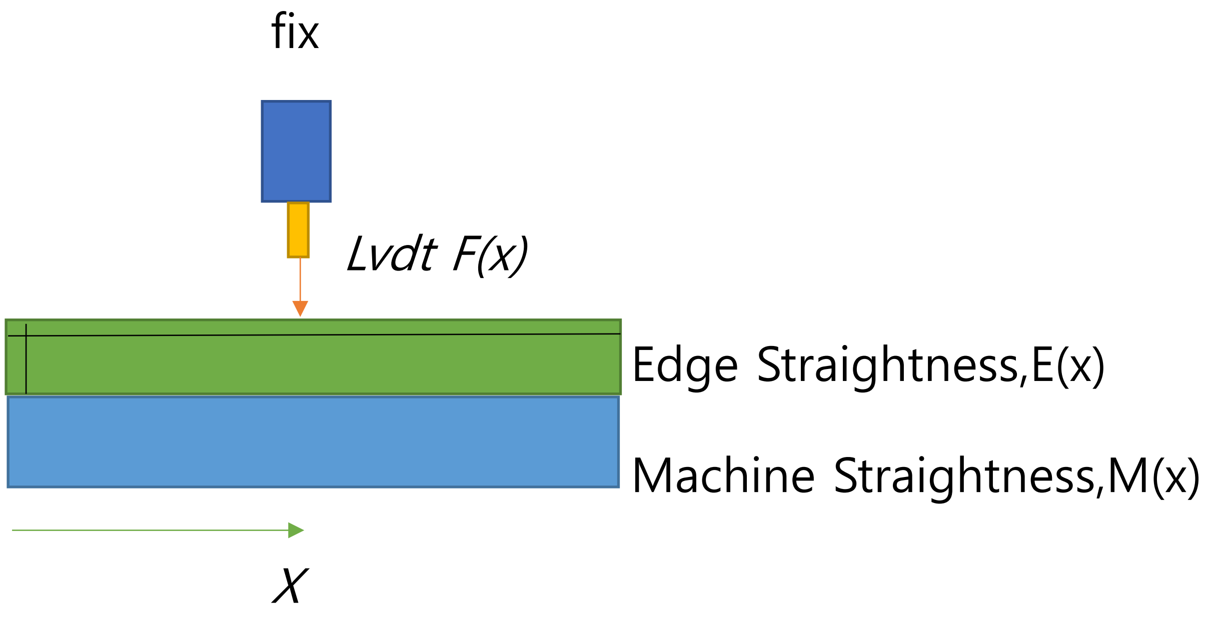
$M(X)$=Machine straightness=$(\underline{R}-\underline{F})/2$

Therefore Edge straightness and Machine straightness can be measured.

2. M type measurement method

:Moving edge type measurement method

Forward measurement



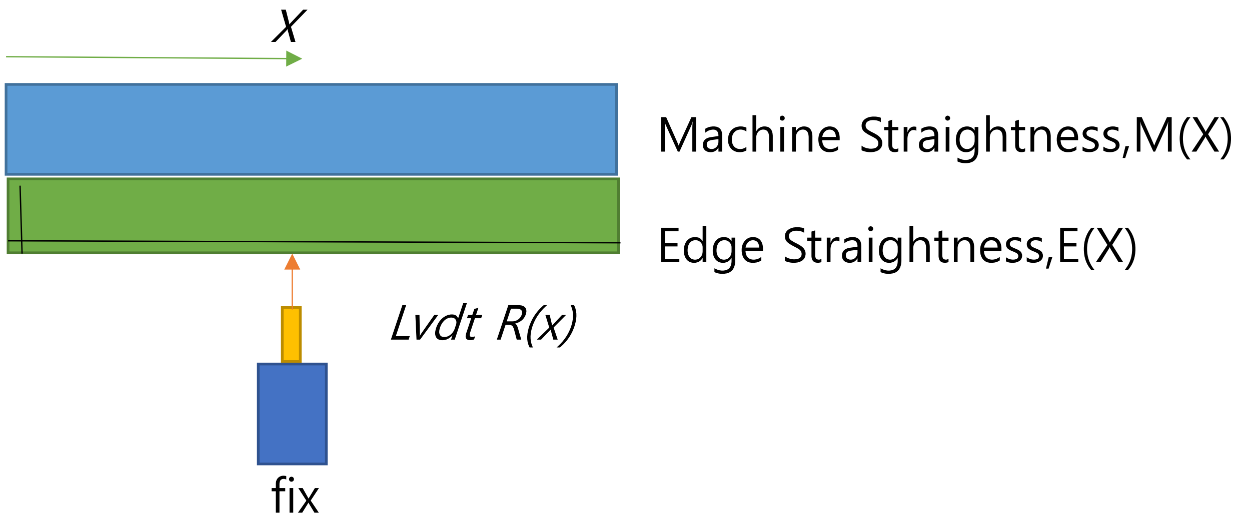
Forward measurement $F(x)=-E(x)-M(x)+a_F x+b_F$

where a_F, b_F are slope and offset of the best fit lines, and physically due to the non-parallelism and stand-offs.

The end points fit, least squares fit, or the minimum zone fit can be used for the best fit reference line.

Thus, $\underline{F} = F(X) - (a_F X+b_F)=-E(X)-M(X) \quad (3)$

Reverse measurement



Reverse measurement $R(X)=-E(X)+M(X)+a_R X+b_R$

where a_R, b_R are slope and offset of the best fit line, and from the non-parallelism and stand-offs.

Similarly, $\underline{R} = R(X) - (a_R X+b_R)=-E(X)+M(X) \quad (4)$

From (3)+(4) and (3)-(4)

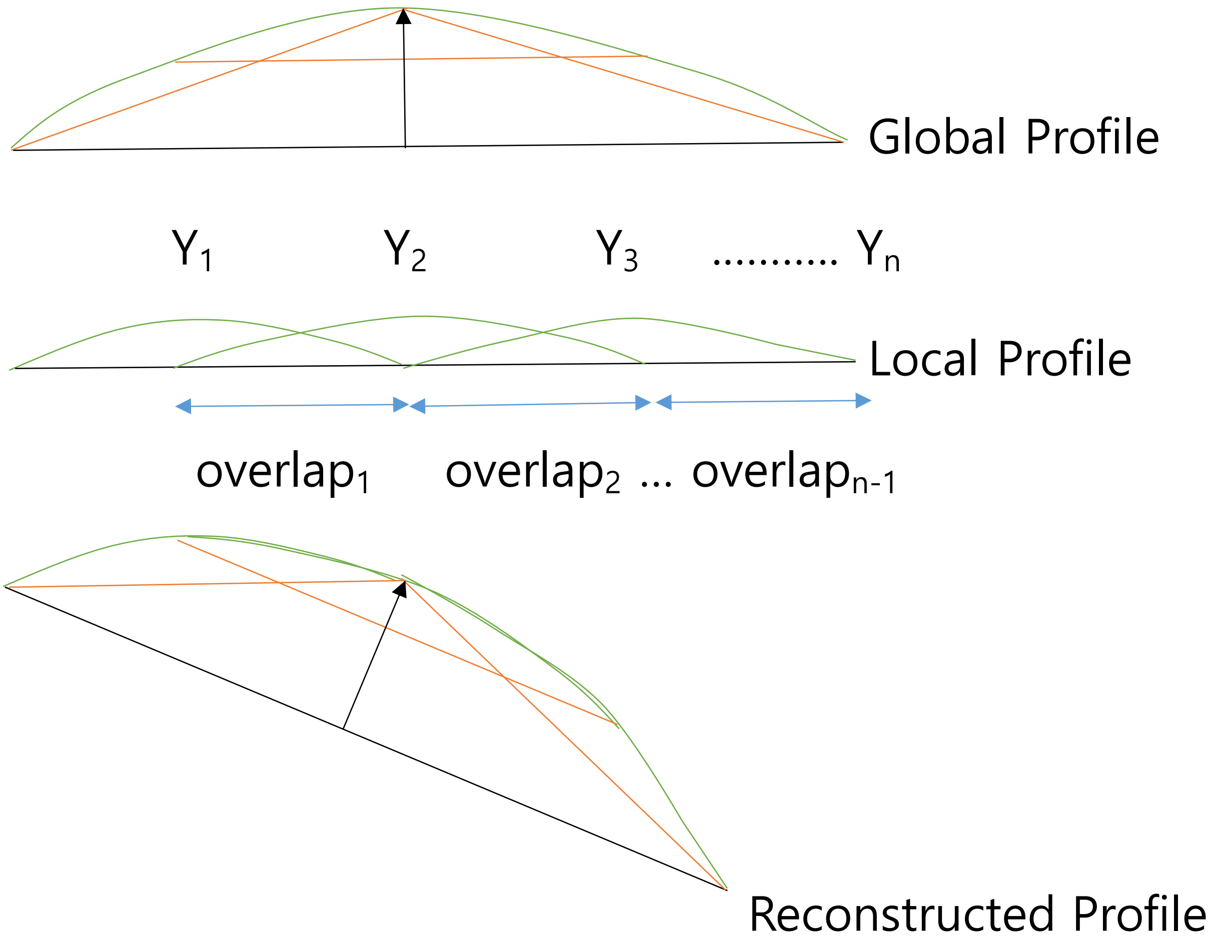
$E(X)=\text{Edge straightness}=-(\underline{F}+\underline{R})/2$

$M(X)=\text{Machine straightness}=(\underline{R}-\underline{F})/2$

Therefore Edge straightness and Machine straightness can be measured.

Profile matching method or stitching method

:To use a short straight edge to measure the straightness of the long travel, by matching the profile over the region overlapped.



When Y_1, Y_2,...Y_n are the straightness measurement data, or local profile, from the short straight edge, the total straightness error, or global profile, can be obtained by the sum of the local straightness error, or local profile.

For overlap$_1$ region, Y_1 must be the same as Y_2, that is, $Y_1 \equiv Y_2$; and any difference is due to the slope and offset of the local straight lines of each local profile.

For the overlap1 region, $Y_1-Y_2=A_1X+B_1$, and A_1, B_1 are the slope and offset to be determined from the best fit line along the distance X over the overlap1 region.

Similarly, for the overlap2 region, $Y_2-Y_3=A_2X+B_2$, and A_2,B_2 are the slope and offset to be determined from the best fit line along the distance X over the overlap 2 region.

Thus, it can be extended to the nth local profile, Yn

$Y_1-Y_2 =A_1X+B_1$

$Y_2-Y_3 =A_2X+B_2$

……

$\underline{Y_{n-1}-Y_n=A_{n-1}X+B_{n-1}} \quad +$

$Y_1 - Y_n = \Sigma(A_kX+B_k)$

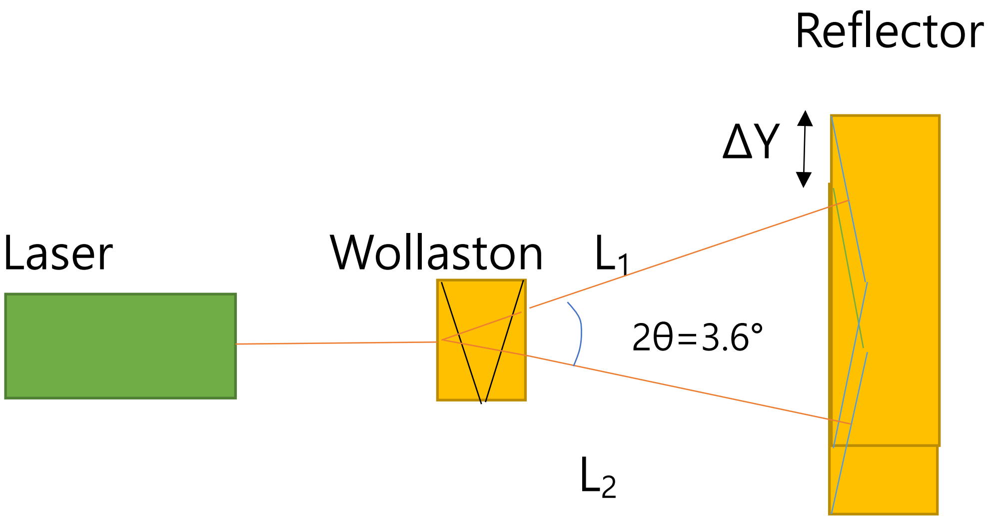
$\therefore\ Y_1=Y_n + \Sigma(A_kX+B_k)$, $k=1,2\ldots n-1$

and n=number of Local profiles. Thus for the local profile, Y_{n}, can be transformed to the global profile reconstructed, Y_1. Then the best fit reference line can be applied to the reconstructed profile, thus the global straightness error can be evaluated.

In this way, the global straightness profile can be obtained by the sum of the local straightness profiles transformed, using the profile matching method. This profile matching method firstly proposed by SNU*, and is sometimes called as the stitching method, and expanded to 2D surface, such as stitching method for semiconductor wafer, giving wide applications or surface metrology.

*Development of Straightness Measurement using Profile Matching Method, H.J.Pahk, J.S.Park, I.J.Yeo, Int.J.Machine Tools and manufacture, Vol.37(2), 135-147, 1997

Straightness Interferometer



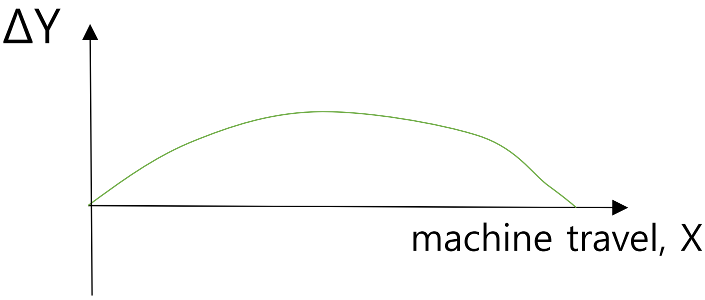
Let L_1^*, L_2^* be the changed length of L_1, L_2 after ΔY movement ;

$L_1^* = L_1 + \Delta Y \cdot \sin\theta$, $L_2^* = L_2 - \Delta Y \cdot \sin\theta$

$L_1^* - L_2^* = L_1 - L_2 + 2\Delta Y \cdot \sin\theta$

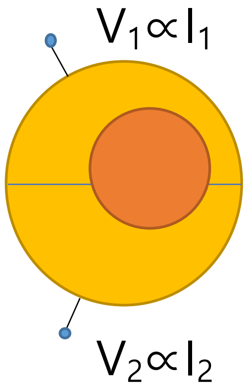
$\therefore \Delta Y = [(L_1^* - L_2^*) - (L_1 - L_2)] / 2\sin\theta$

3-5 times repeat straightness measurements, ΔY, over the machine travel



Tooling laser with Photosensor, Photodiode, CCD

For Bisector Photo Sensor

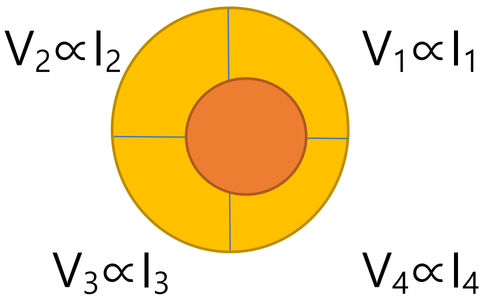


Centroid = $(I_1 - I_2)/(I_1 + I_2) = (V_1 - V_2)/(V_1 + V_2)$,

or Pixel count

∴The straightness error can be measured.

For Quadrant Photo Sensor



X Centroid $=[(I_1+I_4)-(I_2+I_3)]/[I_1+I_2+I_3+I_4]$

$=[(V_1+V_4)-(V_2+V_3)]/[V_1+V_2+V_3+V_4]$

Or, Pixel count

Y Centroid $=[(I_1+I_2)-(I_3+I_4)]/[I_1+I_2+I_3+I_4]$

$=[(V_1+V_2)-(V_3+V_4)]/[V_1+V_2+V_3+V_4]$

Or, Pixel count

$\therefore$Two straightness error components can be measured

This is a simple and convenient measurement, but sensitive to beam fluctuation due to temperature, airflow, especially in the long distance.